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The Effects of a Novel Head-Mounted Symbology on Spatial Disorientation and Flight Performance in U.S. Air Force Pilots



Fred H. Previc¹, Nathan A. Dillon², Rick H. Evans¹, Ryan Maresh², William R. Ercoline¹, & Joseph Fischer¹

¹Wyle, Inc., San Antonio, TX

²U.S. Air Force School of Aerospace Medicine, Wright-Patterson AFB, OH



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**Air Force Research Laboratory
711th Human Performance Wing
School of Aerospace Medicine
Aeromedical Research Department
2510 Fifth St.
Wright-Patterson AFB, OH 45433-7913**

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1.0 SUMMARY

Spatial disorientation (SD) has accounted for about 25% of all Class A mishaps in the U.S. Air Force over the past several decades, with over 40% of fatal mishaps attributed to SD. One way to counter SD is by improving attitude awareness (pitch and roll) and overall spatial orientation through improved primary flight displays. One such display, the X-Motion Device™ (XMD), is a see-through device resembling standard eyewear but with a head-tracker and dual-axis symbology. The purpose of the present study was to compare flight performance, SD conflict perception, and workload in those sorties in which pilots were presented with XMD symbology versus those in which they were not to determine any advantages or disadvantages that may accrue from the XMD symbology. We also assessed the subjective opinions of pilots regarding the X-motion symbology by means of a 13-question survey. Tests were conducted in the gyroflight sustained operations simulator, a four-axis flight simulator with additional SD-producing capabilities. Each participant had a single-day training session and a testing regimen carried out over 2 days. Overall, the XMD symbology had a slight negative effect on overall flight performance, no effect on SD conflict perception and susceptibility, and a slight benefit for attitude awareness based on subjective ratings by our 10 pilots. Based on the results of this study, the current iteration of the XMD symbology is not beneficial to flight performance and may actually limit scanning of primary flight instruments.

2.0 INTRODUCTION

Broadly defined, spatial disorientation (SD) has accounted for ~25% of all Class A mishaps in the U.S. Air Force (USAF) over the past several decades (Ref 1), and recent trends suggest that this is still the case (Ref 2). An even larger percentage of fatal mishaps (>40%) can be attributed to SD (Ref 2).

One way to counter SD is by improving attitude (pitch and roll) awareness and overall spatial orientation through improved primary flight displays. Because many newer aircraft do not include dedicated attitude displays in the central cockpit, most attitude and other primary flight information is presented on head-up displays. The Joint Strike Fighter even has limited flight symbology on its head-mounted display, but its symbology does not include pitch and roll information. Hence, the use of large, ambient, see-through attitude displays has been proposed by many researchers since the early 1980s (Ref 3).

A novel display—the X-Motion Device™, created by AdviTech (San Antonio, TX) and hereafter known as the XMD—is a see-through device resembling standard eyewear but with a head-tracker and dual-axis symbology. The symbology displays two large intersecting lines that depict the orientation of the head relative to gravity (i.e., is head-referenced). In addition to providing continuous orientation information to the pilot, the XMD is also designed to stabilize the vestibular-ocular reflex and facilitate instrument cross-check and viewability in turbulent or disorienting conditions in which unwanted vestibular-ocular movements may occur. The XMD has been tested in a clinical environment and has proven capable of improving vestibular symptoms (e.g., dizziness, spinning, vertigo) and inhibiting the vestibular-ocular reflex (Ref 4).

Spatial disorientation can be simulated in many ways, one of the most realistic of which is the USAF's SD research profile. In this profile, which was used in recent studies of the relationship between sleep deprivation and SD (Ref 5,6), pilots fly a ~19-minute sortie from takeoff to landing and experience eight SD illusions: excess-pitch during takeoff, three

postrotatory illusions upon exiting turns, a sloping cloud deck, a Coriolis illusion due to head tilt during a steep banked turn, a simulated leans during descent, and a sloping runway illusion (see References 5 and 6 for details). In a recent sleep deprivation study, the SD illusions were reported ~50% of the time by USAF pilots, and flight performance was significantly influenced by the sloping cloud deck and sloping runway (Ref 5). In the current study, an additional 13-minute profile (known as Profile 2), consisting of a takeoff, entrance into turbulence, final approach turn, and instrument landing, was used. In addition to measures of overall flight performance, ability to recognize SD conflicts, and flight performance during specific illusions (e.g., bank deviations during a conflict in that same plane, glide slope and course deviations during landing), we measured cognitive workload by presenting auditory warning cues to which the pilot was required to respond.

The purpose of the present study was to compare flight performance, SD conflict perception, and workload in those sorties in which pilots were presented with XMD symbology versus those in which they were not to determine any advantages or disadvantages that may accrue from the XMD symbology. We also assessed the subjective opinions of pilots regarding the X-motion symbology by means of a 13-question survey.

3.0 METHODS

3.1 Participants

The participants were 10 male USAF full-time, Reserve, or simulator instructor pilots between the ages of 24 and 47 years. Pilots were recruited from the San Antonio area, primarily Randolph Air Force Base. Pilots averaged 2747 overall flight hours (range = 450-5100 hours) and 791 hours (range = 90-1550 hours) in the T-6 aircraft, whose aeromodel is replicated by the gyroflight sustained operations simulator (GSOS) used in the present study. All pilots were screened for normal vestibular function using a sharpened Romberg test and had no history of vestibular problems (e.g., dizziness, vertigo). They also had no history of visual deficits and all possessed a Snellen visual acuity of 20/20 or better, without correction or with contact lenses only. Each pilot signed an Informed Consent Document and, if participating in an off-duty capacity, received compensation up to \$300 from Wyle, Inc.

3.2 Apparatus

This study was conducted in the GSOS, a four-axis flight simulator with additional SD-producing capabilities. The GSOS motion has a range of $\pm 25^\circ$ in pitch and roll and 360° in yaw (sustained). The GSOS features subthreshold washout as well as limited vertical heave (± 12 cm). It has a three-channel, noncollimated, out-the-window visual display with a 28° vertical by 120° horizontal field-of-view. The GSOS aeromodel replicates the T-6 aircraft, and the GSOS's reconfigurable instrument panel is programmed to closely approximate that of the T-6. The GSOS is operated and monitored from a control station adjacent to it (see Reference 5 for more details).

The AdviTech XMD is a user-worn, see-through display that currently consists of glasses with the appropriate infrastructure—external power and processor unit, external connector cable, and internal video engine and circuitry—to provide an artificial horizon and vertical reference (Figure 1). The glasses incorporate various miniature accelerometers to continuously measure

head movement relative to gravity. These data are then processed using proprietary software and built-in micro-circuitry and used to display the dual-axis symbology. The XMD displays two head-referenced indicators—the pitch/roll indicator and the head-rotation indicator—but, for technical reasons, the head rotation indicator was caged in our study.

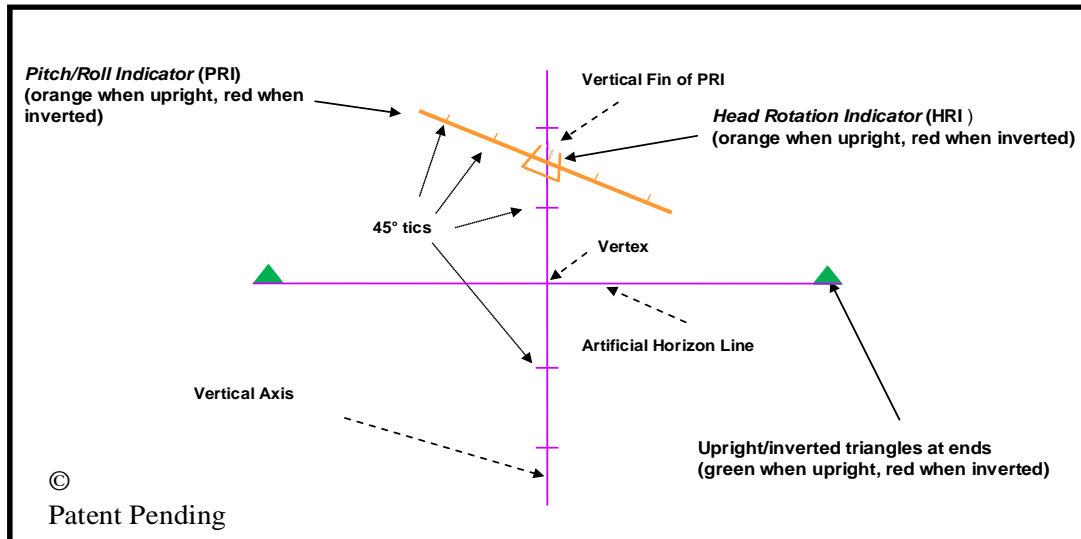


Figure 1. The Symbology Set of the XMD as Employed in the Present Study (the example depicts 70° pitch up and 30° right roll)

3.3 Procedures

For each participant, the study consisted of two phases: a single-day training session and a testing regimen carried out over 2 days. During the training session, which lasted approximately 4 hours, pilots become acquainted with the GSOS simulator during an approximately 15-minute free-fly period. They then donned the XMD eyewear and were instructed on how to properly fit it as well as turn its symbology on and off. Each pilot then proceeded to train on four trials of Profile 1 and two trials of Profile 2. On two training trials Profile 1 contained the eight SD conflicts, and on the other two trials it did not contain any conflicts. On the remaining two profile training trials, pilots flew Profile 2, with the XMD symbology turned on for one trial and turned off for the other. Profile 2 contained ~2 minutes of what would be considered severe turbulence in the aircraft, generated by rapid heaving and semi-random roll and pitch movement and finishing with a pure spinning sensation lasting 20-30 seconds. The spinning was created by a postrotatory mechanism after the cessation of prolonged yawing at 150°/s and led to substantial uncontrolled nystagmus (vestibular-ocular disorganization, or Type III SD) for several seconds. During training, the turbulence was reduced to 33% of its value to prevent pilots from adopting strategies to deal with the full-turbulence profile that they encountered during the actual testing. Profile 2 also required the pilot to perform a simulated instrument landing at Dayton International Airport.

During the two 2-hour test sessions, which occurred on separate days spaced no more than 96 hours apart and at approximately the same time of day, pilots were presented with four trials of Profile 1 (conflict/nonconflict sorties, symbology on/off) and two trials of Profile 2 (symbology on/off). The reason for running both conflict and nonconflict versions of Profile 1

was to enable the effects of specific SD conflicts on flight performance and subjective reports of those conflicts to be compared to a no-conflict baseline, both with and without the XMD symbology. The two versions of Profile 1 and one version of Profile 2 were run during each session in a counterbalanced order, with the sole exception being that the turbulence profile (whether with the XMD or not) always occurred at the end of the session to avoid it affecting performance on Profile 1. During Profile 1, various measures of flight performance were obtained specific to each segment of flight—airspeed (during all seven phases of flight), vertical velocity (four phases), heading (three phases), bank (three phases), altitude (one phase), and glide slope and course deviation (one phase). Each performance measure consisted of root-mean-square error (RMSe) from the specified flight parameter. In addition, as in Reference 5, the ability of pilots to recognize the eight SD conflicts was measured, as well as specific aspects of flight performance during each conflict phase: (1) pitch angle during a simulated pitch-excess illusion during much of the takeoff in Segment 1, (2) bank angle while a sloping cloud deck appeared in the wings-level climb in Segment 3, (3) bank angle during a head-tilt-induced Coriolis illusion in the 45° banked turn in Segment 4, (4) bank RMSe during a simulated leans illusion (subthreshold roll) during the wings-level descent in Segment 5, and (5) glide slope during the visual landing in Segment 7. Finally, pilots' speed (measured by reaction time) and accuracy in detecting a total of eight strategically placed warning signals, consisting of four quick beeps alternating around 1000 Hz, provided a measure of cognitive workload during each sortie.

During Profile 2, pilots performed a takeoff and climb before leveling off at 3000 feet. After level-off, they entered the turbulence—which pilots on average rated as “severe” according to the definitions provided in Air Force Handbook 11-203 (Ref 7)—from either a left or right roll, which reversed the turbulence profiles to reduce the effects of prior exposure. During the turbulence, which lasted for slightly more than 1 minute, heading, altitude, and airspeed RMSe were measured. Approximately 15 seconds after the end of the turbulence, pilots commenced their maneuvering to final approach. Once pilots intersected final approach and were <5 nautical miles from the runway, they began their final descent. From this point to decision height above the runway, pilot performance was measured in terms of airspeed, course deviation, and glide slope deviation. As with Profile 1, pilots were required to detect eight warning signals spaced at key points throughout Profile 2.

At the completion of the profiles, pilots were asked to complete a brief survey concerning the effectiveness of the XMD in maintaining their attitude awareness and overall flight performance in the GSOS. The survey (see Table 1) consisted of 13 items to which the pilot provided a rating of XMD effectiveness ranging from “extremely detrimental” (1) to “extremely beneficial” (7), with “4” being neutral.

4.0 RESULTS

The results of the various flight performance and other measures were analyzed using SPSS (IBM SPSS Inc., New York, NY) (Ref 8). The flight performance results from Profile 1 were analyzed using a two-factor analysis of variance, with the two factors being SD conflict vs. nonconflict flights and XMD vs. no-XMD flights. For Profile 2, which did not have a separate set of SD conflict flights, paired *t*-tests (two-tailed) were used to distinguish flight performance when viewing versus not viewing the XMD symbology.

Table 1. The Survey Used to Assess Pilots' Subjective Ratings of the XMD

| Category | Judgment ^a | Comment |
|--|-----------------------|---------|
| 1. Viewing of cockpit instruments | 1 2 3 4 5 6 7 | |
| 2. Viewing of out-the-window scene | 1 2 3 4 5 6 7 | |
| 3. Cross-check of primary flight instruments | 1 2 3 4 5 6 7 | |
| 4. Performing cockpit tasks other than cross-check | 1 2 3 4 5 6 7 | |
| 5. Reading and interpreting other cockpit displays | 1 2 3 4 5 6 7 | |
| 6. Motion sickness | 1 2 3 4 5 6 7 | |
| 7. Awareness of aircraft pitch | 1 2 3 4 5 6 7 | |
| 8. Awareness of aircraft roll | 1 2 3 4 5 6 7 | |
| 9. Awareness of aircraft yaw | 1 2 3 4 5 6 7 | |
| 10. Unusual attitude recognition | 1 2 3 4 5 6 7 | |
| 11. Overall awareness of aircraft attitude/orientation | 1 2 3 4 5 6 7 | |
| 12. Overall situational awareness | 1 2 3 4 5 6 7 | |
| 13. Overall flight performance | 1 2 3 4 5 6 7 | |

^aJudgment Scale: **1** = *Strongly detrimental*; **2** = *Moderately detrimental*; **3** = *Slightly detrimental*; **4** = *Had no effect*; **5** = *Slightly beneficial*; **6** = *Moderately beneficial*; **7** = *Strongly beneficial*

4.1 Flight Performance Measures

The seven flight measures recorded in the various segments of Profile 1 were averaged to obtain a mean RMSe for each measure. Because the measures recorded during the turbulence and landing phases of Profile 2 were very different in terms of performance measures and flying demands (severe turbulence vs. instrument landing), the six measures from the two Profile 2 segments were analyzed separately. Hence, there were 13 RMSe measures across the two profiles in which comparisons between the XMD and no-XMD symbology conditions were analyzed statistically.

Of the 13 RMSe measures, only 2 were found to be statistically significant for the XMD vs. no-XMD comparison. The first was vertical velocity in Profile 1 ($F[1,9] = 7.58, p = .02$), where RMSe was 474.81 ft/s with and 416.21 ft/s without the XMD symbology, respectively. The second significant outcome involved altitude RMSe in the turbulence phase of Profile 2. Altitude RMSe was 89.82 feet and 61.85 feet in the XMD and no-XMD conditions, respectively ($t[1,9] = 2.88, p = .018$).

There was also a significant effect of conflict vs. no-conflict trials in the glide slope deviation in Profile 1. Because the narrow, upsloping, and fog-shrouded runway was designed to elicit a perception of being too high, glide slope deviated more from the specified 3° in the conflict condition than in the nonconflict condition ($F[1,9] = 7.7, p = .022$), but this difference was unaffected by viewing the XMD symbology.

4.2 Flight Performance During Specific SD Illusions

Analyses were performed for flight performance during five specific conflicts in Profile 1: (1) pitch angle during a portion of the takeoff in Segment 1, in which excess pitch-up tilt occurred; (2) bank angle during an approximately 20-second portion of the wings-level climb in Segment 3 in which a sloping cloud deck was visible while the pilot searched for outside traffic; (3) bank angle while experiencing a Coriolis illusion due a 10-second period of head-down tilt during the 45° turn in Segment 4; (4) RMSe bank error during an 82-second period of simulated leans (subthreshold roll) in Segment 5; and (5) glide slope deviation during the majority of the visual landing performed in Segment 7. Flight performance in the above segments in the conflict flights was measured against flight performance in these same segments during the nonconflict flights, both with and without the XMD symbology. There were no effects of any of the above conflicts on flight performance, with the exception of a greater glide slope deviation in the conflict vs. nonconflict trials (-5.08° vs. -3.87° , respectively) ($F[1,9] = 18.32, p = .002$).

4.3 Perceptual Data

The number of SD conflicts recognized while viewing the XMD symbology (4.5 out of 8) did not differ significantly from the number recognized while not viewing the symbology (4.8 of 8) ($t[9] = .49, p = .638$). The number of tones detected also did not differ between the XMD (7.73 of 8) and no-XMD (7.67 of 8) conditions ($t[9] = .69, p = .509$), presumably because of the high accuracy in both conditions (e.g., a ceiling effect).

4.4 Survey Data

Of a total of 13 questions pertaining to the effects of the XMD symbology, only 2 resulted in a mean difference from the neutral rating of “4” of at least one rating point (see Table 2). Pilots gave a mean rating of 5.3 to “awareness of aircraft roll” (Question #8) and a mean rating of 5.0 to “overall awareness of aircraft attitude/orientation” (Question #11). In both of these cases (and no others), a majority of pilots rated the XMD as beneficial. The ratings for each question were also assessed using t -tests, which showed significant effects against a neutral rating of “4” only for the above questions: ($t[9] = 3.28, p = .009$) for Question #8; ($t[9] = 2.54, p = .032$) for Question #11.

Overall, 3 of the 13 average ratings (all related to viewing of the cockpit instruments or out-the-window scene) were less than 4 and 9 were greater than 4. The lowest rating for the XMD was 3.6 for Question #2 (“viewing of out-the-window scene”). Only one pilot submitted negative ratings to more than half of the questions.

5.0 DISCUSSION

The present study performed a comprehensive test of the effects of the XMD symbology on flight performance, recognition of and susceptibility to SD conflicts, and workload during simulated flight, along with perceived benefits. Overall, the XMD symbology had a slight negative effect on overall flight performance, no effect on SD conflict perception and susceptibility, and a slight benefit for attitude awareness based on subjective ratings by our 10 pilots.

Table 2. Mean and Range of Ratings to Each Survey Question Averaged Across 10 Pilots (4=neutral)

| Category | Mean Rating | Range |
|--|------------------|-------|
| 1. Viewing of cockpit instruments | 3.8 | 3-6 |
| 2. Viewing of out-the-window scene | 3.6 | 2-5 |
| 3. Cross-check of primary flight instruments | 4.1 | 2-7 |
| 4. Performing cockpit tasks other than cross-check | 4.0 | 3-5 |
| 5. Reading and interpreting other cockpit displays | 3.9 | 3-4 |
| 6. Motion sickness | 4.7 | 4-7 |
| 7. Awareness of aircraft pitch | 4.4 | 3-7 |
| 8. Awareness of aircraft roll | 5.3 ^a | 4-7 |
| 9. Awareness of aircraft yaw | 4.4 | 4-7 |
| 10. Unusual attitude recognition | 4.6 | 3-7 |
| 11. Overall awareness of aircraft attitude/orientation | 5.0 ^a | 3-7 |
| 12. Overall situational awareness | 4.6 | 3-6 |
| 13. Overall flight performance | 4.6 | 3-6 |

^aSignificant difference from neutral rating.

The significant decrements in flight performance were for vertical velocity (in Profile 1) and altitude (in the turbulence phase of Profile 2). These displays are not viewed as much as the attitude display during the normal instrument cross-check (Ref 6) and might be more affected by an altered visibility of cockpit displays or an alteration of cockpit scanning, which was a concern of many pilots in the survey. Indeed, pilots generally reported that they had to focus more on the XMD symbology, although this was not reflected in the workload measure. Whether these results in our pilots would have been obtained after much more training and experience with the XMD symbology remains to be investigated.

Although the XMD did not improve bank and pitch performance, most pilots did report that it slightly aided them in awareness of aircraft attitude in general and aircraft roll specifically. Although the XMD is a head-referenced rather than aircraft-referenced display, the survey results suggest that a large head-mounted, aircraft-referenced symbology would also aid aircraft attitude awareness and, if properly implemented, perhaps even improve flight performance. Possible improvements to this XMD would be to aircraft-reference rather than head-reference its symbology and to place it on a monocular headpiece attached to the helmet to provide better see-through visibility.

In summary, this study showed that the current iteration of the XMD symbology is not beneficial to flight performance and may actually limit scanning of primary flight instruments.

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LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|------|---|
| GSOS | gyroflight sustained operations simulator |
| RMSe | root-mean-square error |
| SD | spatial disorientation |
| USAF | United States Air Force |
| XMD | X-Motion Device |